Structuring of embodiment design problem based on the product lifecycle

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Abstract: Early stages of the design process are often based on designers' experience; assumptions and irreversible decisions restricting the solution space are taken. It is difficult to take into account simultaneously every requirement imposed by the different phases of the product life-cycle. In this paper, a method is proposed to perform the analysis of the embodiment design problem. It facilitates the search of the indispensable elements, suitable for structuring the preliminary design phase. Our approach is performed for the relevant life-cycle situations of the product. A four level analysis (need, functions, organic structure and physical behaviours) is proposed. The set of structuring elements allow the design problem definition as a Constraint Satisfaction Problem (CSP).

Keywords: embodiment design; structuring elements; design problem analysis; decision support system; layout; product life-cycle requirements; CSP.

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1 Introduction

At the preliminary design stage, the decisions being taken influence up to 70% of the life-cycle cost (Figure 1). Several methods have been proposed to structure the global design process (Pahl and Beitz, 1996; Dieter, 2000; Ullman, 2003; Aoussat, 1990; Cavailles, 1995). On the other hand, there are few suitable tools to guarantee the relevance of the embodiment solutions (Yannou, 2001). At this design process stage, the following dilemma appears to be of major importance: designers should be lowly constrained in order to be creative (Matthews et al., 2002) and have to be constrained so that the decisions being taken verify the requirements of the design problem. Thus, it is necessary to have parsimonious but precise information (Sebastian, 2003) in order to be able to initiate the formalisation of the solutions and, on the other hand, to be able to make valid decisions engaging the durability of the choices.

Figure 1 Evolution of committed costs during design process

Source: Zimmer and Zablit (2001).
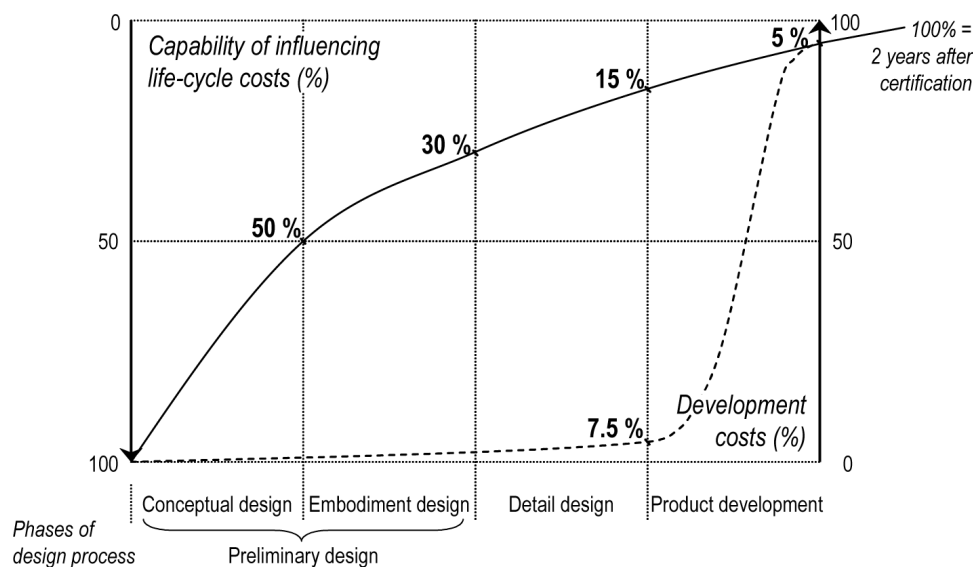
The systematic approach (Pahl and Beitz, 1996) is rather widespread; however difficulties can arise in the early stages of the classical process of product design. They are mainly related to the simultaneous integration of the requirements stemming from various life-cycle stages, and to decisions that designers have to take early in the design process (Chakrabarti et al., 1992).

First of all, several relevant concepts are rising from conceptual design. Designers have to perform a first choice among these concepts. In order to limit the duration of the design process and to decrease risks, they tend to focus very early towards a solution they can handle. Thus, interesting alternatives might be eliminated, because they are unknown, unused, unusual or non-evaluated.

Then, starting from a chosen concept, embodiment design aims to define rough arrangements and structural dimensions of the indented product, in accordance with technical, economic and aesthetic considerations (Pahl and Beitz, 1996). Designers have to identify key parameters relevant for this definition. Even if there are few parameters and standard elements for a simple mechanism, there is however a great number of possible combinations. Then, designers must make choices (Hicks and Culley, 2002), based on their own experiences. They operate on a try-corrections mode.

So, design iterations cannot be avoided between the conceptual and the embodiment design phases, before reaching design solutions (Ashby, 2000; Hicks and Culley, 2002). This iterative process appears clearly in many models of the literature (Tate and Nordlund, 1996). Moreover, the embodiment solutions are depending on these initial decisions, which greatly limit the field of design investigations.

Another difficulty in an integrated engineering context is the confrontation, as soon as possible, between the different points of view of the design actors and technical skills (technical data, marketing data, company identity, environmental data, ergonomics, cultural and symbolic aspects). Constraints, specific to the product life-cycle phases, must be also taken into account.

More to the point, at a stage where the knowledge is uncertain, most of existing computer-aided tools are based on models requiring the complete geometrical definition of the product. In order to evaluate a design alternative, the performances of several configurations should be estimated rather than a particular solution performance, which might be, moreover, evaluated too late within the design process.

2 Constraint-based embodiment design problem modelling

A decision support system for the embodiment design phase has been developed to overcome these difficulties, by coupling a numeric CSP (constraint satisfaction problem) solver and a knowledge base (Fischer et al., 2002). An approach has been proposed in order to investigate the performances of these tools within known design processes (Scaravetti et al., 2003). It starts from relevant concepts and leads to feasible embodiment solutions. Figure 2 shows the stages and job-status of embodiment design enhanced by the use of the decision support system for a mechanical device design (Scaravetti et al., 2004):

- this process starts from two relevant working structures

- an analysis phase leads to identify the structuring characteristics of the embodiment design problem

- once the model is written, the CSP solver gives the solutions (a solution is a combination of structuring parameters, which check all the listed constraints)

- finally, the embodiment solutions are sorted, using an objective function.

Figure 2   Different job status of the enhanced embodiment design phase
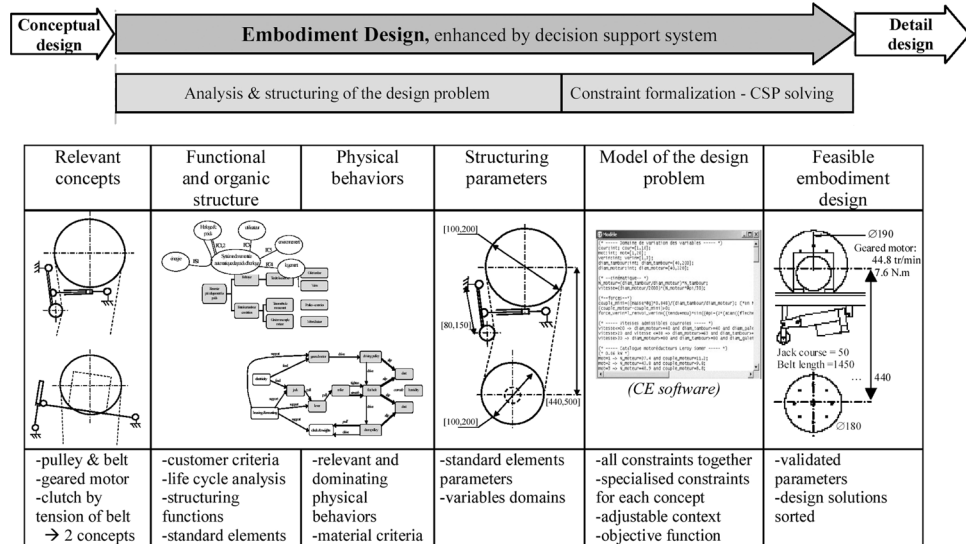
The use of this decision support system supposes the transcription of the design problem as a set of constraints (equality, inequality, logical rule). The CSP solver finds out combinations of variables satisfying all the constraints. This approach avoids the a priori decision-making and also shuns dismissing solutions; indeed causality and sequentiality during calculations are avoided.

Instead of starting with one retained concept, several concepts can be described by a set of specific constraints. The choice between several concepts is performed through the numerical processing of the constraint satisfaction problem.

All the conditions that determine the product characteristics are also translated into constraints: geometry, functional requirements criteria and physical behaviours for the relevant life-cycle stages, standard elements, technical skill rules, manufacturing constraint, cost evaluations. The variables can belong to continuous domains; thus, no variable is a priori fixed and the potentialities related to the concepts are preserved. The variables can also be discrete, enumerated and tabulated (catalogues).

The difficulty inherent in this approach is to correctly formalise the knowledge base (set of constraints) so that this base is coherent, non-redundant and complete. Designers require a method for capturing the information in the form of knowledge (Theodosiou and Sapidis, 2004).

We propose an analysis and structuring methodology of the design problem, in order to facilitate the formulation of constraints by designers: this approach is based on a four level analysis (need, functional, structural, physical) leading to determine the relevant parameters of design (like a designer does using his expertise) and to the identification of structuring characteristics and functions, translated later into constraints.

During the first steps of a design project, it is necessary to reduce the extent of the design problem. Designers do not take into account every requirement of the design problem and only some functions are selected. Their reasoning is based on structuring functions that initiate the design process and leads to the first validated product architecture.

In the same way, necessary and sufficient elements are identified in order to limit the embodiment design problem complexity. These elements are called structuring functions and criteria. On the contrary, the systematic approach (Pahl and Beitz, 1996) looks for the exhaustiveness. The purpose of design methodologies is to guide designers and specify a design process with stages and milestones. We do not propose a new design method, but a method to select these structuring elements useful for the design embodiment phase.

3 A four level approach for the design problem analysis and structuring

The proposed methodology for the identification of structuring elements recovers information in functional performance specifications, physical behaviours analysis and technical skill rules. This methodology is based on classical tools performing need analysis, functional and structural analysis. Functional analysis (AFNOR, 1990–1991) is usually used in an industrial context. The regulation documentation necessary for quality certifications and for the reliability, availability, safety assessments are based on functional analysis. It is also useful for tasks identification in project management. Thus, our approach based on classical tools does not necessitate new competences.

The search for structuring elements is performed by an approach based on a four level problem analysis: need, functional, organic, and physical (Figure 3). For each step, a selection method of structuring elements is proposed.

Figure 3 Stages of the method and tools for identification of the structuring elements
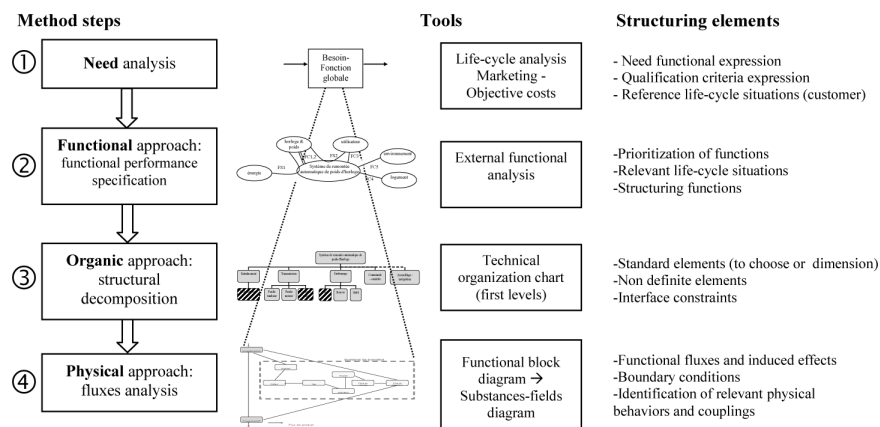
4 Need analysis (step #1)

Need analysis is related to a customer interested in the product. The customer can be:

- the end user of the product to be designed; the internal functions do not concern him and some criteria will not be a part of his qualification criteria.

- a company department, an applicant, a control service, a certifier: he is interested in the criteria related to internal functions and to expected physical behaviours.

They will be expressed during the next steps.

4.1   Need expression

A rational and efficient design method starts with an exhaustive formulation of the expressed or implicit user's need (AFNOR, 1990–1991). At this stage, the customer often formulates its need in marketing and economic terms; the expected results and time limits are also expressed.

The functional analysis translates and integrates the need expression for the end user, the customer and the designer (Prudhomme et al., 2003). However, the need expressed on a functional form, does not prejudge of the architecture of the system to be designed. So, the solutions field is not restricted.

The global function is always structuring, but may not be the most structuring one.

4.2   Product life-cycle analysis

Figure 4 enumerates the life-cycle situations related to the stages of the product life-cycle.

Figure 4   Product life-cycle and the corresponding life-cycle situations
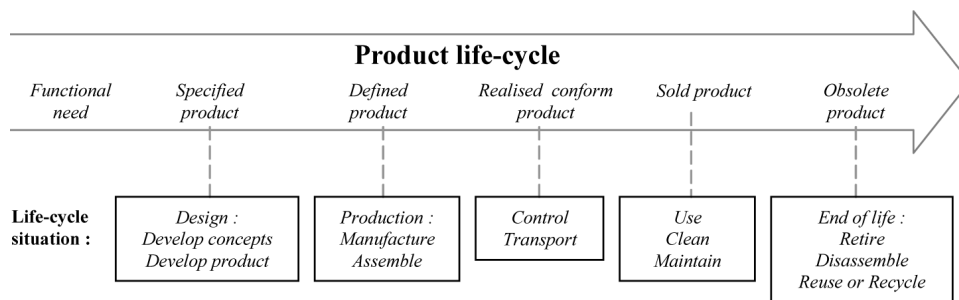
The functional performance specifications expressed by the customer defines expected features of the product. In most cases, it does not systematically mention the life-cycle situations of the product. In that case, it is necessary to determine these situations from the expressed functions. Then, they are organised into a hierarchy from the hierarchical organisation of the functions.

These reference life-cycle situations for the customer, initially expressed or not, will be a part of structuring situations.

New life-cycle situations emerge due to the evolution of the political, economic, industrial contexts, like end of life and recycling for example. These evolutions make prematurely obsolete the products, which did not integrate during their design the constraints connected to these life-cycle situations. These new requirements become inescapable and are imposed for example by standards.

4.3   Qualification criteria for customer

The customer has to express the relevance criteria of the design. These criteria will qualify the proposed design.

Table 1 enumerates qualification criteria by categories. It indicates the used variables and criteria, as well as the way of writing the constraints.

- The *technological functional criteria* concern the performances expected by customer and safety requirements. The structural criteria concern the constitution of the product, its resistance to the environment (atmosphere, vibrations, corrosion), its complexity. The product complexity (PC) can be defined as $PC = \Sigma_j \times F_j$: j is the level of the functional decomposition and F_j is the number of functions at this level (Bashir and Thompson, 1999). The used functional description is coherent with the technical organisation chart used in the step #3 (see Figure 5): these functions correspond to the functions of every functional block. PC will be calculated later. A limit value can be fixed thanks to a repository and previous projects experience.

- The various costs are enumerated in the *economic criteria*.

- The indicators of environmental impact and of sustainable development are also integrated in the qualification criteria. Several specialised indicators exist. More globally, the eco-efficiency indicator (Janin, 2000; Verfaillie and Bidwell, 2000) compares the economic performance and the environmental performance. It is a relative measurement of the environmental impact. Such indicators can be:

    Mass of sold product or net sales per

    - Energy consumption
    - Material consumption
    - Greenhouse gas emissions

- The *qualification criteria relevant for the company and marketing* concerns development times, design risks and product perception.

The project duration can be estimated from the product complexity PC (Bashir and Thompson, 1999):

    Time (hours) $= A \times PC \ D^{0.85}$

- 'A' is a constant depending on the company size and on the information circulation. It can vary from 30 for a small firm with a good communication, up to 150 for a big company with an average communication (Ullman, 2003).

- 'D' is related to project difficulty (1: little difficult, using known technologies; 2: difficult, few new technologies; 3: very difficult).

Larson and Kusiak (1996) and, Sarbacker and Ishii (1997) give indications onto the design risks and their consequences, from the designer point of view; the consequences are always related to the costs and project duration. The index of risk priority (IRP) allows to quantify the risks connected to a system or to a component (Landy, 2002). The risk is defined as a magnitude with two dimensions (characterising one dreaded event): The probability of occurrence and the gravity of the consequences (defined in terms of loss of performance or financial loss) (Grenouilleau et al., 1999).

Table 1   Qualification criteria for customer and characterisation

Qualification criteria:	Characterisation: variables and criteria	Constraint (quantitative evaluation)	Origin x,y, ..	Qualitative evaluation	Ref
Technological criteria					
Functional criteria					
Expected performances	Efficiency\power\physical parameters (force, speed, temperature, pressure …)	Parameter $\in$ [x,y] Parameter$\in$ {x, y, z}	(1)		
	Productivity (number of actions per time unit)	Parameter > x			
Regulation	Criteria based on standards	Parameter $\in$ [x, y] Parameter < x	(2)		
Minimal life expectancy	MTTF: mean time to (first) failure	MTTF > x	(1)		Ligeron and Lyonnet (1992)
Reliability	MTBF: mean time between failures	MTBF > x	(1)		Ligeron and Lyonnet (1992)
Availability	Indicator of operational availability: $D^{op} = MTBF/MTBF + MTTR$	$1 > D^{op} > x$	(1)		Monchy (2000)
Maintainability	MTTR: mean time to repair rate of standard components	MTTR > x	(1)		Ligeron and Lyonnet (1992)
	Ease of cleaning			Yes/no	
Security	FMECA criteria: Criticality = severity level×proba. occurrence× proba. not detection	Criticality < x	(3)		Landy (2002) Garin (1994)
	Certification requirements	Criterion < x	(2)		
Robustness	S/N (signal/noise)	S/N maxi	(3)		Taguchi (2003)
Autonomy	Energetic (operation life)	Autonomy > x	(1)		
	Do not necessitate human intervention			Yes\no	
Structural criteria					
Mass	Total mass, maximum (or minimum)	Mass < x	(1)		
Encumbrance	Minimum dimensions (or maximum)	Dimension > x	(1) (2)		
	Volume coefficient of the packaging: VCP = parallelopiped packaging volume/contents volume	1 < VPC < x	(1) (2)		CEN, European Committee for Standardisation (2000)

Table 1   Qualification criteria for customer and characterisation (continued)

Qualification criteria	Characterisation :variables and criteria	Constraint (quantitative evaluation)	Origin x,y, ..	Qualitative evaluation	Ref
Structural criteria					
Resistance to the environment	Maxi level of temperature\pressure\humidity\salinity\vibrations (amplitude, frequency) …	Temperature < x…	(1)		
Complexity	Product complexity: $PC = \Sigma_j \times F_j$…	$PC < PC_{ref.}$ $PC < PC_{min}$	(3)		Bashir and Thompson (1999)
Economic criteria					
Industrialisation cost	Costs equipments + machines \workforce	Cost < x	(5)		
Production cost	Cost machine functioning\production unit\workforce	Cost < x	(5)		
Ownership cost	Energy consumption Life-cycle cost (acquisition, operation, maintenance)	Cost < x Consumption < x Energetic contents < x	(1) (4)		Millet (2003)
Maintenance cost	Operation cost\parts	Cost < x	(1) (4)		
Recycling cost	Dismantling costs\treatment …	Cost <x	(2)		
Objective cost	Product cost (components, materials, manufacturing)	Cost < x	Value analysis		
Investment capacity	Necessary investment\possible investment	Cost < x	(5)		
Recyclability	% total recyclable mass Irreversibility of the connections (removable\irremovable) Compatibility of materials (yes\no) Number of materials	%mass < %maxi Material number<x	(2)	Removable compatible Yes\No	
Sustainable development	Eco-efficiency indicator = product value/environmental impact	Indicator < x	(2)		Janin (2000) Verfaillie and Bidwell (2000)

Table 1   Qualification criteria for customer and characterisation (continued)

Qualification criteria	Characterisation: variables and criteria	Constraint (quantitative evaluation)	Origin x,y, ..	Qualitative evaluation	Ref
Economic criteria					
Environmental impact (in the various life-cycle phases : manufacturing, distribution, use, end of life …)	Power consumption	Consumption < x	(1) (4)		
	Water and material consumption	Consumption < x	(2)		
	Resources impact indicator	RII < x			Brent and Visser (2004)
	Emissions of gas and pollutants, waste:	Emission < x	(2)		Millet (2003)
	impact indicator 'greenhouse effect': kg of CO_2 equivalents emitted				
	impact indicator 'destruction ozone layer': kg of CFC11 equivalents emitted				
	Heat generation: heat flux	Flux < x	(2)		
	Humidity generation: flux of material	Flux < x	(2)		
Qualification criteria for company, marketing					
Project duration	Time (h) = A×PC×D$^{0.85}$	Duration < x	(5)		Bashir and Thompson (1999)
	% new elements (cf technical organisation chart)	% new elements < x			
Risks: design, costs, time	IRP = gravity×occurrence×validation	IRP < x	(5)		Landy (2002)
	Possible overruns (costs, time limits)	Overrun < x			
Startup	Necessary time\qualification	Time < x	(1) (4)	Qualification yes\no	
	Temperature setting …	Time < x			
Environmental impact (nuisances)	Level of generated noise	Noise level < x	(2)		
	Generation of smell			Yes\no	
	Visual nuisance			Yes\no	
User perception	Associated variables	Variable < x			Dore et al. (2003)

Legend: Origin of the constraint limit: (1) Functional performance specifications; (2) Standards and regulations; (3) R&D choice; (4) Marketing and (5) Financial and temporal management of project.

4.4 Relevance indicators

From the relevant concepts, several feasible architectures can be proposed. The relevance indicators give elements to designers to make choices and take decisions.

The adaptable or negotiable or quantifiable qualification criteria (for customer) are then translated into relevance indicators.

Relevance indicators are structuring elements, integrated within the model and calculated. They are suitable to calculate performance indicators (see Section 5.4) and they highlight closeness or distance compared to a reference. They are integrated into objective function(s), useful to sort the embodiment solutions.

5 Functional approach (Step #2)

When external functional analysis is realised for all life-cycle situations, functions and external environments are exhaustively enumerated. We wish to retain the relevant life-cycle situations, organise the functions into a hierarchy and extract those, which are structuring for the problem of preliminary design.

5.1 Choosing relevant life-cycle situations

First of all, the life-cycle situations deducted from the customer's functional specifications are relevant. They are explicitly expressed or deducted from the satisfaction of the global function or from the functional specifications.

After the external functional analysis, risky life-cycle situations are selected. They concern safety (reliability, maintainability, availability). The more important ones are situations badly mastered and identified thanks to experience feedbacks. Life-cycle situations where product or environment can be modified must be selected. For example: 'prolonged stop', 'functioning in aggressive or polluting environment' or any situations susceptible to modify the state of the product. The situation 'maintenance' is necessary to ensure the good functioning of the product.

'Design' and 'manufacturing' also retained life-cycle situations, because designers take into account constraints related to manufacturing possibilities (state of the art, technical skills rules).

All these relevant life-cycle situations influence steps #2 and #4 of the structuring and analysis of the design problem. Indeed, these two steps are realised only for these situations.

5.2 Structuring functions

Among the functions stemming from functional analysis, the structuring ones are enumerated into Table 2. The constraints can be expressed in an explicit way when a particular industry is targeted. An example concerning fluids cooling is developed in Bouchama et al. (2003).

Table 2   Different types of structuring functions

Types of structuring functions	
Function related to qualification criteria for customer	
Function with no flexibility	
Risky function	Already known problems, negative feedbacks
	Function never realised
	Precision or an exactness imposed by the customer
	Energy management
Imperative constraint function	System behaviour or performances
	Standard or regulation to respect: technical or industrial normative documents related to person or material protection.
	Interchangeability
	Prohibition or imposition of the principle solution:
	industrial context, usable technologies
	qualified concept (Aeronautics; chemical and pharmaceutical industries)
	industrial property
	Known risk
	Environmental criteria (Janin, 2000):
	legal requirements, standards : impact on environment (release, pollution, waste, noise, consumption of resources, recyclability), re-use, reprocessing, stocking
	demountability, with the aim of the materials separation (materials, connections)
	Environmental costs: equipments, backfitting, materials (type and number of different materials), assemblies, resumption of packagings
	Material:
	imposition: food, ageing, resistance (mechanical, chemical, thermal, etc.)
	Cost
	Structural constraints
	Limit time
	Material:
	unavailability
	prohibition (danger, standards…), in the product or in the process
	dependence material/process (if process is imposed)
	supply, supplier
	Manufacturing functions (manufacturability, facility of assembly, treatment of surface, etc.)

Table 2   Different types of structuring functions (continued)

Types of structuring functions

Technical skill rules	Company know-how rules
	Technical repository
	Design rules (guidelines)
	Manufacturing rules specific to the company know-how
	General rules
	Embodiment design rules (Pahl and Beitz, 1996)
	Manufacturing rules
	Technical skill rules related to the application of codes
	Way to design, banned solutions
	Manufacturing modes
	Controls, maintenance

For the structuring functions, assessment criteria and variables are expressed. An assessment criterion allows to appreciate the way a function is filled or a constraint is satisfied (AFNOR, 1990–1991). The level and the flexibility of a criterion can be translated on a constraint form.

A redundancy can appear between these assessment criteria and qualification criteria for customers. The redundancy is useful to guarantee the exhaustiveness of the identification of the structuring elements.

- *Functions with no flexibility* are identified thanks to functional performance specifications when assessment criteria are enumerated (level, flexibility, limit …). Functions with low or nil level flexibility are retained as structuring functions.

- *Risky functions* (on the technical level) are identified thanks to already known problems, negative feedbacks, etc. For that purpose, it is necessary to capitalise knowledge and to know how to reuse it. According to Ullman (2003), when knowledge is weak they are critical functions. A risky function can result from a precision or an exactness imposed by the customer.

A function that was never realised might be risky. Risk analysis takes into account the novelty, complexity, arisen events and gravity of the consequences related to the product design (Leroy and Signoret, 1992).

A functional risk might occur when the energy is badly managed, entailing a dysfunction (Desroches, 1999).

- *Imperative constraint functions* are imposed by the external environments (technology, market, situation and choices of the company, etc.). On one hand, there are constraint functions (AFNOR, 1990–1991) concerning system behaviour or performances (legal regulations, imposed materials or solutions, etc.). On the other hand, some structural constraints do not concern directly the realisation of a function (time limits, supplying, etc.).

- *Technical skill rules* are identified through functional analysis, for the life-cycle situations 'design' and/or 'manufacturing' and/or control and/or maintenance. For example, these rules intervene as soon as that the company has to manufacture 'with the potential of the company':

- *Know-how rules of the company*. Design rules, calculus rules, manufacturing rules, cost or duration estimation rules, etc.

  - A manufacturer has technical reports, capitalising the know-how and defining criteria to be respected. For a car manufacturer for example: ground clearance, protection of the electric wires, seat command (ergonomics), design recommendations for recycling, etc.

  - Guidelines for the environmental integration are used by some manufacturers (Janin, 2000). They enumerate the banned or advised materials, instructions of conception in order to facilitate their dismantling, their recycling, etc.

  - Manufacturing rules connected to the company know-how, induce design constraints (curvature radius of pipes, minimum crankcases thicknesses, etc.).

- *Global design rules*. Embodiment design rules (Pahl and Beitz, 1996) are concerned with form choices appropriated to manufacturing processes or facilitating the assembly.

- Technical skill rules indicate the type of tool or material to be used, in order to obtain for example, a surface specification or a tolerance.

- Technical skill rules related to the application of professional codes. These dimensioning codes are related to a specific product or industry sector: CODAP (pressure vessels), EUROCODE, BAEL (civil engineering), PS (seismic), RCCM, FEM, CM66, ASME, NEIGE, VENT, etc.

The codes impose the way to design, the banned solutions, the manufacturing modes, the controls and maintenance to be made. They also impose the calculation rules connected to the materials being used and prescribed manufacturing processes. In some cases, the physical models are supplied. This type of constraint is raised in the stage #4 (physical approach).

These enumerated structuring functions generate constraints (equality, inequality, logical rules), intervals or enumerations among which variables will be chosen.

5.3 *Relevance indicators, from the designer's point of view*

Technical rules may impose causality between the variables, that is to say, a procedure or an algorithm to treat the design problem. Designer criteria might not be expressed in the functional performance specifications. These intermediate elements are useful to compare some design alternatives. Designer criteria are relevance indicators:

- Relevant criterion in the realisation of a technical function. The designer may add parameters which are not expressed by the customer, but allow him to qualify a function.

- The functioning risk can be estimated by the distance compared to a reference (standard, rule, experience feedback, test on prototype) with the performance indicator.

5.4 Performance indicator

Once identified the relevance indicators stemming from the qualification criteria for the customer and the designer's relevance indicators, we compare them with a reference.

A performance indicator highlights relevance indicator's closeness or distance compared to a reference.

A performance indicator must be minimised.

- $Ip = I/I\ ref$, if the performance corresponds to the distance compared to the reference. In that case, it is connected, for instance, with a risk of operation.

- $Ip = I\ ref/I$, if the performance corresponds to the closeness compared to the reference. In that case, it is connected, for instance, with an optimisation process.

The reference (I ref) can be:

- *Fixed*. An evaluated element, imposed by the customer, by standards, etc. It is a fixed reference, intrinsic to the problem and independent from the context. If it can be expressed, it is preferable to use it.

  A risk can be evaluated by knowing a reference. For example, the distance of a parameter can be quantified by comparison to a standard.
  The degree of change can also be quantified. In certain cases of re-design, minimising changes is needed.

- *Relative*. The minimal or maximal value of a relevance indicator among a set of results: For a given configuration and a given context, the solutions can be compared with each other regarding the indicator.

So, the performance indicators allow:

- *The comparison regarding a customer reference*: it necessitates to overcome the calculation of the indicator corresponding to this reference.

- The comparison of the solutions between them. If a criterion cannot be defined completely, it is however necessary to identify relevant parameters relative to the criterion.

A comparison between concepts can be (Ullman, 2003):

- *absolute*: each concept is compared to objectives using criteria

- *relative*: concepts are compared by using measurements defined by the criteria.
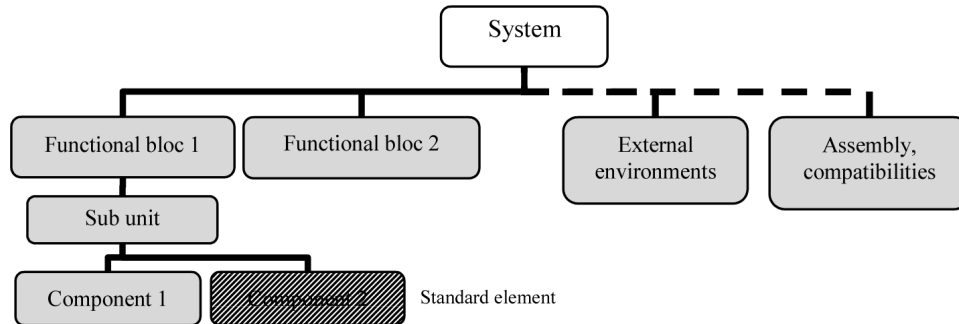

6   Organic approach (Step #3)

The product concept is defined in a first technical organisation chart by assembling functional blocks (Figure 5).

However, only the first levels define the product at the conceptual stage. Beyond the first levels, other choices are realised, during the embodiment design phase.

This chart allows to identify and to define elements in the Table 3.

Figure 5 Technical organisation chart

Table 3 Structuring organic elements

Structuring elements	*Characterisation*

Standard element — To be chosen

    Intrinsic constraints :   dimensions

                interfaces

                energy supply

    Constraints related to life-cycle situations:

-     constraints of use
-     warehousing, transport, etc.

    Susceptibility to harmful factors

To be dimensioned

    Dimensioning rules

Non-defined elements

Interface constraints — Wanted, useful

Contact:
geometry, encumbrance, connection, fixationassembly
tension, amperage
energetic

Distant:
 computational

    thermal (radiation)

Non-wished (harmful)

    Contact: energetic (exchanges, losses)

    Distant: electromagnetic compatibility (interference)

        thermal (radiation), etc.

For example, a domestic vacuum cleaner with a disposable bag can be decomposed in three main functional blocs (pipe, fan, bag) and two external environments (air, dust).

The *standard elements* are to be chosen or dimensioned:

- The standard components to be chosen are components ready-to-use belonging to catalogues. Their choice is made on relevant parameters, relative to the functions they perform.

  They impose their intrinsic constraints (dimensional constraints, interface constraints, energy supply, etc.): these variables are identified in the problem, but they can take only standard values. On the other hand, some constraints are associated to various life-cycle situations, not directly connected to the functions they fulfil, and given by the manufacturers (constraints of use, warehousing or transport, etc.). It is also necessary to investigate their sensitivity to harmful factors.

- The standard elements to be dimensioned are concepts already mastered by the company (known functional blocks, where only some parameters are adjusted). Dimensioning rules exist for these typical elements; they arise from the company knowledge, from technical books or from professional dimensioning standards (CODAP, TEMA, etc.).

- Design of *non-defined elements* cannot be avoided and are thus structuring. They have to be dimensioned.

The design risk is estimated (Landy, 2002) and choices have to be made according to the anticipated risk. The badly known alternatives are dismissed.

- The relations between the system and the external environments are enumerated. The *interface constraints* express the compatibility between the elements or between one element and its environments. Some interface constraints may be already identified at the previous step.

Various types of interfaces are (Cavailles, 1995):

- *functional interface (compatibility of mechanical links, electric or electronic links)*: connections, fixation; assembly; tensions, amperages; signals (input, output, form); computer interface (protocols, languages)

- *physical interface, compatibility between characteristics of nearby constituents*: electromagnetic, geometrical compatibility (encumbrance, assembly …)

For the interfaces, the connection between two elements must be checked and the conservation laws of fluxes must be satisfied.

7 Physical approach (Step #4)

The model of the design problem has to contain a description of the relevant physical behaviours. In order to enumerate them, the structuring variables and behaviour of the system have to be investigated in an exhaustive way. For that purpose, functional block diagrams (FBD) and substances-fields graph (SFG) are used.

Table 4 summarises the structuring elements related to the physical approach.

Table 4   Structuring elements related to the physical approach

Structuring element	Characterisation
Key elements, in which the main functional flux passes through	
Relevant and dominating physical behaviour	Conservation laws
	of mass
	of energy (heat, mechanical or deformation energy, etc.)
	of the impulse
	of electric charge
	Boundary conditions
	Induced relations of coupling
	pressure losses
	models of contact, friction
	electromagnetic interaction
	deformation, fastening, creep
	clogging etc.
Durability of components	
Calculation rules imposed by the professional codes	
Material criteria	Mechanical functions (rigidity, elasticity, resistance to fatigue, wear, shocks, etc.)
	Specific functions: thermal, chemical (resistance to corrosion, etc.), electric, optical, magnetic, acoustic, etc.

The FBD is a representation of the path of the functional fluxes through a system corresponding to a life-cycle situation. These fluxes connect the external environments to the system or the system components together (internal fluxes). The designer has to choose the level of the system representation. Indeed, FBD is suitable to describe the whole system or only a functional block. At a detailed level, its use may be complex. A FBD corresponds to each design solution.

Completing each function induces a flux (Ullman, 2003) and fluxes may be of various nature: energy, material, information, user esteem. The functional flux path corresponding to the functional conditions can be visualised using the FBD. The main functional fluxes pass through structuring elements.

The contact graph lists exhaustively the connections between functional blocks. The distant actions are estimated using a systematic questionnaire. The effects of gravity, mobile parts (effects of inertia or centrifugal), non-material fields (sounds, ultrasounds, optics, electric, radiation, magnetic, etc.) are successively examined.

However, the FBD does not identify the interactions between the transported materials and the induced effects. The FBD solely describes the functional fluxes passing through the components. Moreover, only the useful functional components appear within the FBD, whereas the effects quoted above are not taken into account. The physical behaviours are described more precisely with substances-fields graph (SFG) (Savransky, 2000).

SFG is suitable to integrate the transported materials or present materials into the system, and to take into account the generated fluxes and the effects induced by these fluxes. A systematic list of generated fluxes and induced effects has been proposed (MAL'IN, 2003). TRIZ theory differentiates the useful or insufficient functions and the unwanted effects (harmful effects).

Figure 6 displays the evolution from a given FBD (partial) to a SFG. These graphs concern the functions 'to suck up and store the dust' for the domestic vacuum cleaner. We found the functional blocks identified in the previous step (Figure 7).

Figure 6   From FBD (6(a)) to SFG (6(b)), for a vacuum cleaner
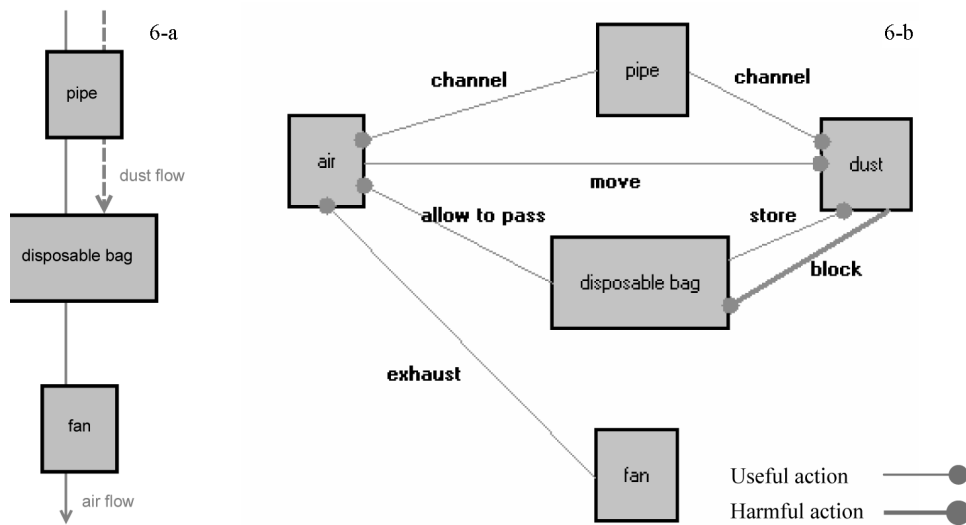
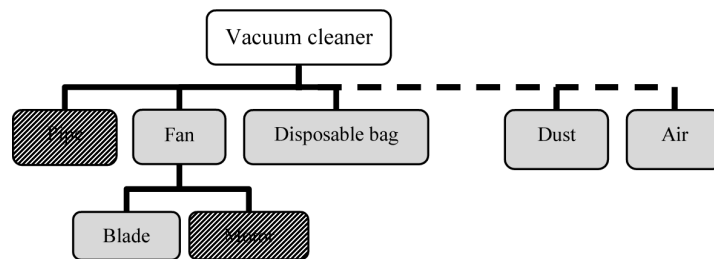**Figure 7**   Technical organisation chart of a vacuum cleaner

Figure 6(a) presents the different fluxes of system: the fan generates an air-flow through the pipe and the porous bag. This air-flow transports the dust to the bag. The FBD (Figure 6(a)) provides exclusively information in term of material fluxes (air and dust). More precise elements would necessitate coming down at the lower systemic level for the disposable bag.

SFG (Figure 6(b)) displays the 'substances' of the system (components and elements transported by the fluxes) and the actions between the substances called 'fields'. The actions are useful (air moves the dust) or harmful (dust clogs the disposable bag holes, the bag clogging perturb the air flux).

These actions are characterised by physical behaviours. For example, the generated air flux is related to a pressure gradient (state-variable of the air) allowing the transport of the dust.

These physical behaviours are structuring for the design problem. Tables (like Table 1), give an exhaustive vision of fluxes generated by the gradients of state-variables and their induced effects. These tables are available during the definition of the graphs with the software tool MAL'IN (2003) (online help).

These graphs have to be interpreted to determine the constraints of the design problem. The functional fluxes are achieved through physical phenomena. At this stage, designers have to choose, among the set of identified phenomena, the physical behaviours that can be neglected. These choices are subjective and appeal to the designers' experience.

The relevant and dominating physical behaviours are highlighted by this approach. Each physical flow is related to one or several constraints:

- Fields are translated by continuity conditions between the substances. The conditions of the flux passage are identified through the physical phenomena corresponding to interaction between substances and determine the boundary conditions.

- Fluxes are interpreted by behaviour laws or/and physical conservation laws. Fluxes can convey material or energy. Balances must be written (mass conservation, energy conservation, etc.).

Some fluxes result from gradients of state-variables such as temperature or pressure. These fluxes may induce non-wished effects such as pressure losses, dilation, creep, deformation, clogging, etc. This phenomena identification process gives the opportunity to express the durability of components. Complementary material criteria related to mechanical functions (rigidity, elasticity, etc.) or to specific functions (thermal, chemical …) may result from this process.

System behaviours may be also determined using professional codes (step #2). In these codes, the calculation rules and physical models may be supplied to the designer: the physical behaviours are translated in a parsimonious way in agreement with the dimensioning needs of the embodiment design.

The physical phenomena identified below lead to the definition of relevant variables. In the vacuum cleaner example, the harmful action 'bag clogging' is related to a physical behaviour described using the relevant variables: bag porosity, bag volume.

8   Recapitulation of structuring elements of the product life-cycle

The constraints specific to certain phases of the product life-cycle initiate the identification approach of structuring elements during the preliminary design:

- Structuring life-cycle situations of the product are identified (step #1). During steps #2 and #4, tools are deployed only for these situations of the life-cycle.

- Specific constraints corresponding to certain life-cycle situations are displayed through the following structuring elements:

- *design*: qualification criteria for company, technical skill rules, imperative constraint functions
- *manufacturing*: technical skill rules, economical criteria
- *supply of components and possible materials*: imperative constraint functions
- *marketing*: economical criteria, marketing criteria
- *use (situation often the most described by the customer and the functional specifications)*: performance criteria, structural and economical criteria, imperative constraint functions, physical behaviours
- *control, maintenance*: economical criteria, technical skill rules
- *beneficiation, recycling*: economical and marketing criteria, imperative constraint functions.

- Constraints specific to life-cycle situations of the standard elements are identified (transport, use, etc.). They are supplied by the manufacturers.

All the items listed above take into account the constraints related to the life-cycle of the product in the definition of the embodiment design problem.

The set of solutions satisfying all these constraints defines the field of solutions.

9 Conclusion

Based on functional analysis, a method has been proposed to help designers to define and enumerate the structuring elements in the early phases of the design process. This method is involved in the preliminary analysis of a design problem and leads to a set of structuring functions, criteria and components. These elements are those that are necessary and sufficient for the preliminary design phase.

After performing the life-cycle analysis, an analysis divided into four stages has to be carried out:

- need analysis
- functional analysis
- organic analysis
- physics analysis.

Several tables defining an exhaustive enumeration of structuring elements have been proposed. The quality of the functional and physical analysis determines the performances of the results obtained by this method.

An example of application for a mechanical device (see Scaravetti et al., 2004) illustrates this method and has been involved in the aid to choice (choice between several concepts of solution and choice of components) and in the search of feasible embodiments. An improvement of the design process duration was observed thanks to the reduction of the iterations. The choices carried out also facilitate the detail design. Finally, the choice performed within the field of embodiment solutions based on an objective function, maximises the performances expected by the customer (physical behaviour, cost).

These works have been involved in a global project aiming to develop decision-making tools for preliminary design:

- the software MAL'IN (Methods for Innovation Aid) is being developed in our laboratory

- the software CONSTRAINT EXPLORER within the framework of the RNTL project CO_2 (national network of software technologies: Design and Constraint Programming).

This project CO_2 gathers Dassault Aviation, CRIL Technology, TREFLE and LIPSI laboratories (interested in design) and artificial intelligence laboratories: LINA and LIP6.

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